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The role of prediction in mental processing: A process approach

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ABSTRACT

Although prediction plays a prominent role in mental processing, we have only limited understanding of how the brain generates and employs predictions. This paper develops a theoretical framework in three steps. First I propose a process model that describes how predictions are produced and are linked to behavior. Subsequently I describe a generative mechanism, consisting of the selective amplification of neural dynamics in the context of boundary conditions. I hypothesize that this mechanism is active as a process engine in every mental process, and that therefore each mental process proceeds in two stages: (i) the formation of process boundary conditions; (ii) the bringing about of the process function by the operation – within the boundary conditions – of a relatively 'blind' generative process. Thirdly, from this hypothesis I derive a strategy for describing processes formally. The result is a multilevel framework that may also be useful for studying mental processes in general.

1. Introduction

There is consensus about the importance of prediction in mental processing, but no broadly accepted theory is available that explains how the central nervous system (CNS) generates and employs predictions, and how this CNS function has evolved. In order to address these issues this paper develops a multilevel process model of the mental mechanisms that underlie behavior. This relates to a system-level approach, which means that the focus is on the functions of processes rather than on their neurophysiological mechanisms.

The process model is developed from a biological perspective in the sense that it applies to all animals with a CNS, and that mental functions are supposed to be related to facing the challenges that life imposes on the individual regarding survival and reproduction. In this perspective, using predictions is a specific strategy employed by the CNS for accomplishing its task of orchestrating actions that improve the chances of survival. Prominent in that strategy is the descriptive and predictive model of the environment on which the organism relies for its goal-directed behavior.

In 2003 Karl Friston made an important contribution to the so-called predictive brain approach of mental processing by describing the perception process as a cascade of inference loops. According to that description, in each loop the incoming sensory information is compared with predictions that have been generated in earlier loops, and detected differences are employed for adjusting the predictions. Friston also showed that this cascade can be described in terms of hierarchical predictive coding, which is a form of Bayesian probability calculus (Friston, 2003). This mathematical process description makes it possible to formulate quantitative hypotheses that can be tested experimentally (Clark, 2013; Hohwy, 2013).

Moreover Friston proposed that action could be described as an active inference that brings prediction of percepts and actual observation closer to each other, or in his own words: 'much innate orientating and tracking behavior is simply a reflection of the brain's inherent tendency to maintain a predictable sensory input' (Friston, 2003). This proposal has received some criticism (Bickhard, in press b; Clark, 2013), because it does not address some of the aspects of action that are highly relevant for survival and reproduction. For instance, according to the proposed description the playful behavior of a child could be explicated as the consequence of explaining away the child's sensory inputs. One of the important aspects that is ignored in this description is the presence of a positive decision bias in the child's mind that not only activates its playful behavior, but also promotes curiosity, exploration and learning *per se* (Singh, Lewis, Barto, & Sorg, 2010).

This paper develops a general framework for mental processing in the context of which different relevant aspects of action can be

Abbreviations: CNS, central nervous system; OFM, organic forward model of the environment; BANS, boundary condition-determined active noise shaping.

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addressed. The framework is centered on anticipation, which in turn is based on prediction. For developing this framework the forward model method is employed, a method that has been applied during the past decades for tackling a wide variety of problems in cognition, perception, robotics and computer vision (e.g. Grush, 2004; Rao & Ballard, 1997; Wolpert, Ghahramani, & Jordan, 1995; Wolpert & Kawato, 1998). These studies have led to what are known as enactivist formulations of perception – such as the theory on sensory-motor contingencies – that take an embodied approach and regard perception as probing the environment (e.g. O'Regan & Noë, 2001; Varela, Thompson, & Rosch, 1991).

The framework has important aspects in common with the interactivist approach developed by Donald Campbell and Mark Bickhard (Bickhard, 2009, in press a & b; Bickhard & Campbell, 2003). Both approaches are process-based instead of substance-oriented. In addition, both approaches provide an alternative for what is often characterized as the input-processor model of brain function. Finally, in both frameworks the focus on future possibilities, i.e., anticipation, is an essential element, and normativity is considered to be of vital importance; however, the model developed here is more specific about the processes by which normativity is achieved. More similarities will appear throughout the paper. Because of these similarities the proposed framework can be tagged in two ways: as a predictive brain approach with the special feature that it is specific regarding normativity, and as an interactivist model with emphasis on anticipation. The most noticeable difference between the two approaches is in the basic argumentation: the present paper mainly argues from biological plausibility with survival as the main goal, while in the interactivist model this argument plays a less prominent part.

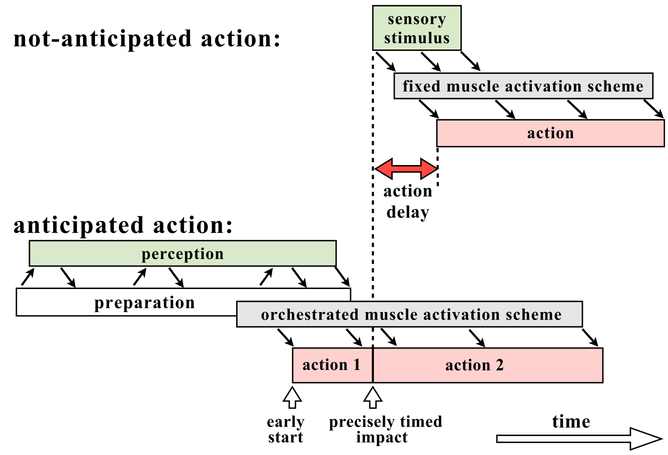

Fig. 1. Flow diagram showing how anticipation improves the accuracy of action timing. Top: Without anticipation. A sensory stimulus triggers a fixed response scheme in accordance with which the action is executed. The time needed for signal transport and signal processing causes action delay. Bottom: The action is prepared in advance, which includes perceptual activity; the early start of the action compensates for signal delay, so precise timing of the crucial part of the action can be achieved. An example is the bird of prey that intercepts a small bird in flight: 'action 1' is the swoop towards the prey, which is so precisely aimed and timed that impact actually occurs; during 'action 2', the bird secures the prey.

2. A process model of how predictions are generated and used

This section focuses on anticipation, which is the process of orchestrating action in advance. It discusses the function of anticipation, its evolution, the role of prediction in it, and how prediction is produced.

2.1. *The function and evolution of anticipation*

For an animal, anticipation has the major advantage that it allows very precise timing of actions such as the interception of a fast moving prey or the escape from an attacker. As Fig. 1 explains, a crucial factor for precise timing is the compensation of the action delay caused by time-consuming neural processes such as the processing of sensory signals by the CNS and the transmission of signals from the sensor to the CNS, and from the CNS to the muscles.

Anticipation also has other benefits: it provides the opportunity to avoid risks, to recognize opportunities on time, and to notice mistakes so that the animal can adapt its behavioral strategies accordingly. The latter makes the creature antifragile, which means that exposure to disturbances improves its capabilities (Taleb, 2012). Also at basic processing level anticipation has advantages: incomplete perceptual information may be filled in from prediction, which enhances the effectiveness of the perception process under harsh conditions, and it allows filtering out irrelevant sensory data, as will be discussed below. For more benefits see e.g. Wolpert et al., 1995. Because reduction of action delay has a direct and significant impact on survival, this benefit is likely to have been the main driving power for the development – during brain evolution – of anticipation as a key function of the CNS.

Organisms that cannot anticipate are entirely dependent on the forces exerted on them from the surroundings; an example is seaweed that is passively moved around by the tide. In stark contrast, an anticipating animal can plan and shape its own course of action because it is able to manipulate time and space in its mind; in this way it can escape from imprisonment in here-and-now causality.

2.2. *Anticipation builds on simulation processes*

Anticipation can only improve the chances of survival if adequate action choices can be made before the action is executed. This implies that the CNS must be able to develop a notion about how an intended action can be expected to unfold, and in particular about what the action consequences will be. I follow Germund Hesslow's proposal that action predictions are produced by means of action simulation processes (Hesslow, 2012). An action simulation process consists of a swift and sketchy mental exploration of the course of the intended action with a degree of detail that is just good enough for making an adequate action choice. In terms of probability calculus: the simulation process reduces the uncertainty regarding future mental states to an acceptable level.

Within the simulation process an embodied valuation process – which will be described in Section 2.5.1 – is active that produces an indication of the extent to which the expected action outcome contributes to the welfare of the animal; this makes the simulation normative.

Simulated actions take place – imaginatively – in an environment that may be different from the present surroundings. The estimation of this remote environment requires a second simulation activity: the simulation of that environment. A relevant consideration in that context is that as an animal moves through its environment, many aspects of the surroundings change only gradually, so it would be a waste of effort to produce a new simulation of the environment for every action simulation. It is more efficient – and therefore more likely – for the CNS to employ the following strategy: (i) it produces – by means of simulation – one comprehensive and realistic model of all the relevant aspects of the present environment; (ii) it continually updates this model by means of ongoing observation of the surroundings; (iii) for every specific action preparation, it derives the required environmental information from this model by means of a swift and dedicated extrapolation. I call the sophisticated model of the environment: the 'organic forward model of the environment', or OFM. The OFM seems similar to what Bickhard calls the 'situation knowledge web' (Bickhard, 2009).

In this perspective, every goal-directed action is based on the OFM. So action is *not* directly based on the sensory stimuli received from the physical environment; instead of guiding action, perception merely updates the OFM. This view is supported by, e.g., the observation of the prey catching behavior of dragonflies (Combes, 2014). Note that sensory impressions *an sich* are meaningless; they become meaningful by means of their integration within the OFM.

The fact that action preparation strictly depends on the OFM implies that an extremely reliable mechanism must be active that keeps the OFM continually tuned to the environment. Since this tuning can only be achieved by means of interaction with the environment, that interaction is an indispensible element of the OFM approach; this provides a link with the interactivist framework (Bickhard, 2009).

The strict dependence of action preparation on the OFM has a conceptual consequence. The frugal nature of CNS operation makes it plausible that the CNS maintains no other models of the environment than the one that it needs for action orchestration, which is the OFM. Therefore, what one experiences as one's environment is *not* the physical environment but one's OFM, which may be supplemented by meaningless fresh sensory impressions. This is not a new insight: for instance Ernst von Glasersfeld came to a similar conclusion, which he called the radical constructivist worldview (Glasersfeld, 1995). The independence of one's sense of reality from perception can be confirmed by a simple experiment: when one closes the eyes visual details disappear, but one still has a fairly realistic idea available about what the world around looks like, and about how objects are arranged there, which is one's OFM.

In this perspective, the term 'perceptual presence' – which means that the objects of perception are experienced as real, as obviously belonging to the world (Seth, 2014) – is a *contradictio in terminis* since the words 'perceptual' and 'presence' represent two issues that are not directly related. Stated differently, in the constructivist perspective supported here the direct coupling between perception and the experienced surrounding – which most people intuitively assume – is an illusion.

2.3. Properties of the OFM

The OFM is a rather complicated mental construction: not only does it contain models of the physical objects that are supposedly present in the surroundings, enriched with attributes such as hardness and permanence, but it also comprises estimations of how these objects move, interact and will change, and it provides information about past experiences with the objects. Especially the human OFM also contains models of abstract and cultural entities. Note that the estimations about the future do not arise from clairvoyance but are extrapolations from earlier experiences and previously made mental simulations.

The effectiveness of anticipation critically relies on the quality of the OFM, so in order to be able to anticipate adequately at all times and in varying circumstances the OFM needs to be continually coherent, efficient, adaptable and well updated. The processes that construct the OFM and keep it up and running in accordance with these requirements probably account for a significant part of the brain's baseline activity (e.g., Raichle & Snyder, 2007).

As regards its content, the OFM seems to have much in common with the 'counterfactual-rich generative model' introduced by Anil Seth (Seth, 2014). Note that the correspondence with Seth's approach is restricted to this aspect: as was discussed above, the idea that perception and awareness of the environment are directly coupled – which Seth assumes – is rejected here.

2.4. Processes that produce and sustain the OFM

This section describes two elementary mental processes that are involved in generating and maintaining the OFM.

2.4.1. Objectification

'Object concepts' are expectations about issues and objects that are supposed to be present in the physical and cultural environments; they are time-independent and invariant under a wide range of environmental conditions and activities (Bickhard, in press a). Object concepts are the building blocks of the OFM; they have also been called models, heuristics, prior beliefs or sensorimotor contingencies (O'Regan & Noë, 2001).

Having object concepts available greatly enhances the effectiveness of anticipation because the CNS can handle these relatively rugged and ready-for-use mental entities far more effectively than the fleeting and often complicated signal patterns that produce sensory impressions. Arranging object concepts into a hierarchical organization – which is the OFM – enhances the effectiveness of CNS operation further. The process of generating and organizing object concepts is known as 'objectification' (Piaget, 1954).

The OFM is well adapted to the physical and cultural environments in which it developed because most object concepts are created from experiences and are fact-checked by means of perception every time they are employed in action. The OFM construction process is subject to two major limitations. Its result – the OFM content – is restricted to what has been experienced or taught. The other restriction is that each adaptation step must build on the previous state of the OFM, which means that only adaptations are possible regarding issues that are 'one step removed' from previous knowledge. In terms of probability calculus, this may be compared to belief updating in Bayesian formulations, where previous knowledge represents prior beliefs, and adaptations constitute posterior inferences (Friston, private communication).

2.4.2. Perception

The construction and maintenance of the OFM depends on perception. The forward model view of mental processing implies that a distinction needs to be made between two main classes of perceptual activity, which I call: 'unprepared perception' and 'prepared perception' respectively.

In the unprepared mode of perception, a salient sensory stimulus – a sharp sound, a sudden movement in the peripheral field of view, or a penetrating smell – has direct and unconditional access to the CNS via mechanisms that are genetically determined. These stimuli are called salient because they may indicate the presence of imminent danger, a mate or prey, which is information that is highly relevant for survival and reproduction. In the CNS this type of stimulus may trigger the orchestration of a reflex, which is an immediate and unconditional response in the form of a movement and/or the arousal of attention. It is likely that unprepared perception mechanisms evolved synchronously with the development of sensors, long before prepared perception emerged.

Prepared perception is an active search for information in the environment; besides the delivery of sensor signals it also comprises actions that improve the perception such as orienting the head, removing objects that are in the way, and shifting the attention. Its primary function is updating the OFM, *not* guiding action directly. A prepared perception activity is triggered by the detection of an unacceptable uncertainty within the OFM (Gottlieb, Oudeyer, Lopes, & Baranes, 2013); prepared perception reduces that uncertainty. Since prepared perception is indispensable for adequate anticipation, both are likely to have co-evolved during brain evolution.

Because the purpose of a prepared perception activity is available in advance, the CNS can develop an expectation about the function and relevance of what will be perceived. This prior knowledge is most useful, since it allows blocking irrelevant sensory data at an early stage of the perception process based on its expected relevance, and it makes it possible to integrate sensory information within the OFM on the basis of its expected function. Both measures enhance the effectiveness of anticipation considerably.

Since the world is hardly ever what one expects it to be, prepared perception should not depend too strictly on what is predicted. One should at least be able to cope with 'mild surprises', perceptions that are close to expectation. I propose that the following neural-level mechanism is instrumental in achieving that.

A general property of neural networks is that the random spiking of individual neurons introduces iterant dynamics of neural activity, which is also called self-organized criticality (Friston, Breakspear, & Deco, 2012; McDonnell & Ward, 2011; Rolls & Deco, 2010). For convenience, I refer to this random neural activity as 'noise'. Noise signals disturb the OFM, so a 'noise repair process' must be continually active that restores the coherence of the OFM; the process that underlies this mechanism will be discussed in Section 3. This repair mechanism also restores OFM coherence after it has been disturbed by the arrival of an unexpected sensory signal – provided that its divergence from what is expected is not too large; the effect of that restoration process is that it integrates mild surprises within the OFM.

2.5. Making decisions

This section discusses how the OFM is employed in the action decision process.

2.5.1. Normativity by means of embodied valuation

Normativity is of vital importance: it is for instance required for making an adequate 'fight or flight' decision. This paragraph proposes an underlying mechanism; the next paragraph describes how that mechanism is instrumental in action preparation.

Action decisions can only be expected to improve the chances of survival if a decision criterion is available that bears relevance to survival; moreover, in situations where delay of action would be dangerous the immediate accessibility of this criterion is of vital importance. Unfortunately there seems no process theory available that adequately deals with these two aspects. Since insight in how choices are made is an indispensable element of any theory on mental processing, a decision valuation mechanism that duly addresses both aspects will be hypothesized here.

A problem is that effectively estimating how well an intended action will contribute to survival is likely to be way beyond the imaginative power of an animal. A practical and relevant alternative is that the animal considers – instead of survival – the more proximate target 'physical wellbeing'. This is a practical criterion since every individual can experience the physical wellbeing of their body; this criterion also seems to be sufficiently relevant because pain and sickness (absence of wellbeing) correlate well with reduced chances of survival, as is supported by the experimental finding that animals that have experienced sickness immediately after having eaten certain food, henceforth refuse to eat the same or similar food (Garcia, Lasiter, Bermudezrattoni, & Deems, 1985).

Making an estimation of physical wellbeing means that along with each action simulation an additional simulation activity is performed that considers the consequences that the intended action might have regarding physical wellbeing. I follow Anil Seth by assuming that this simulation builds on a combination of physiological change and cognitive appraisal (Seth, 2013). In process terms this means that two complementary mechanisms cooperate: I propose that a primary mechanism guards the relevance, and a secondary mechanism ensures sufficient decision speed. The primary mechanism is based on interoception, the sense of the internal physiological condition of the body (Seth, 2013). This mechanism employs chemical information about that condition in the form of particles such as neurotransmitters, hormones and immune system cells, which reach the brain via blood veins and lymphatic vessels. The secondary mechanism performs a neural emulation of the primary mechanism in case an immediate decision is desired (Damasio, 1999); it is quicker because neural signals travel faster than particles in a blood stream. The secondary mechanism is trained by the primary mechanism during ontogenetic development; it seems likely that after this training the primary mechanism remains active in the background for checking – and if necessary for correcting – the activities of the secondary mechanism. Note that in this view all decisions are embodied since they depend – directly or indirectly – on the primary valuation mechanism; this also counts for rational decisions.

The simulation of physical wellbeing produces a 'decision value', a quantitative indication of the desirability of the intended action that allows making decisions. A decision value that is delivered solely by the primary mechanism I call a 'somatic response', or more loosely: the 'gut feeling' that indicates whether one 'feels good' or 'feels bad' about the subject matter. This type of response is univocal, even in complex situations; therefore, apart from inadequate biases that may be present, the primary valuation mechanism is generally a rather reliable basis for action. In contrast, a decision value produced by the secondary valuation mechanism may depend on a variety of rational arguments, so it is generally far less univocal.

2.5.2. The decision process

The flow diagram of an action decision process in Fig. 2 shows how two action simulations, each having a valuation process operating in parallel, contribute to reaching a decision. The environmental context for these simulations is provided by the OFM that is continually updated by prepared perception. Evaluation of the produced values leads to the choice of the most desirable action. Subsequently a 'go/no go' function determines whether the chosen action is to be executed or not: it is executed only if the associated value indicates that this action is sufficiently desirable.

The decision to execute an action is accompanied by an initiative

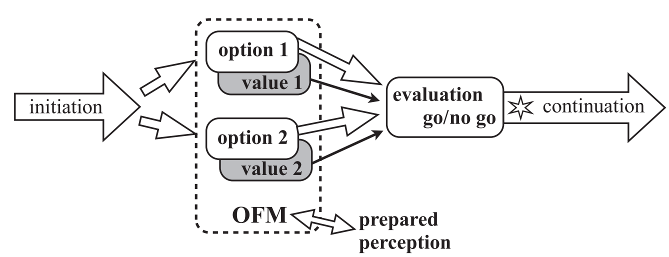

Fig. 2. Flow diagram of an action decision process. Two action options are simulated in the context of the OFM that is continually updated by prepared perception. For each action option a value is generated that reflects the estimated contribution to the chances of survival. The evaluation phase identifies the most desirable action option by comparing the values. The chosen action is executed only if its value is sufficiently high; this decision is symbolized by 'go/no go'.

– symbolized in Fig. 2 by a star – that prepares the body and the mind for the action. Examples of action preparation processes are: (i) emotion-related processes that optimize the physiology of the body for the action, and (ii) the pre-activation of the neural networks that are expected to be involved in perceptual activities during the action, which involves messages known as 'efferent copies' of the outgoing signal (Wolpert et al., 1995). These processes are likely to have evolved since they improve the chances of survival by minimizing action delay.

Decision processes are essential elements of action preparation. Parts of action preparation may be described – similar to the way Friston describes perception – as a cascade, or a nested assembly, of decision loops, where the decision outcome in one loop provides boundary conditions for decision-making in the next loop.

In conclusion, three types of predictions are important for making decisions: the OFM, which is elaborate and relatively stable, and the simulations of action options (Section 2.2) and of physical wellbeing (Section 2.5.1), which are numerous, evanescent and sketchy.

2.5.3. Memory

In the constructivist perspective, a memory is an active mental construction of what is supposed to have happened in the past, based on the OFM information that is currently available. Experimental evidence supports this view (e.g., Schacter, Guerin, & Jacques, 2011). The construction mechanism behind memory retrieval is probably similar to the mechanism that constructs object concepts (Section 2.4.1). Note that this type of memory differs fundamentally from the address-based memory found in digital computers.

2.6. Process structure

Language-related mental processes can be given an appropriate place in this process model by assuming that two different structures exist in the organization of mental processes. This assumption comes close to the 'system 1- system 2' segregation proposed by Daniel Kahneman (Kahneman, 2011); a main difference lies in the choice of what 'makes the difference': Kahneman regards attention, not process structure, to be decisive.

I call the two different process structures 'serial' and 'organic', respectively. A serial structure is a relatively simple, almost linear, arrangement of items such as the sequence of words in a sentence. Organic structure is more complicated: it looks like an irregular spider web. Organic processes typically contain several parallel process pathways with numerous interconnections and crossings; examples are action simulation and action orchestration. Most animal mental activity consists of organic mental processing. I speculate that the main reason why humans are capable of sophisticated verbal communication, rational thinking and long-term planning is that they acquired exceptional serial processing skills during evolution.

To illustrate the difference, consider a woman who wants to cross a busy traffic road. She observes the passing vehicles. Based on those observations she 'senses' – by means of sketchy organic simulations – the trajectories that the vehicles will follow during the next few seconds, and her options for crossing the road. When she tells later about this episode she employs serial language. Of interest here is that a stark contrast exists between the seemingly effortless manner in which she carries out this organic action preparation, and how extremely hard it is to describe that process verbally in full detail.

One of the ways in which serial and organic mental processes can cooperate is that serial signal patterns impose a serial structure on the organization of a group of organic processes, which Andy Clark calls 'scaffolding' (Clark, 1997). Serial signal patterns may play this dominant role because on average they are more stable than organic signal patterns, a property that – in turn – follows from their relatively low number of process bifurcations that makes them more easily sustainable. An example of this cooperation is the automatic shaping of the hand when reaching for a cup of coffee: an organic orchestration of muscle activities that is guided by the serial plan of having coffee.

Rational thoughts and explicit understanding are products of serial mental processes; intuition is a product of organic mental processing. Organic mental processing takes the lion's share of the action orchestration activity that occurs within the CNS. Importantly, organic processes seem to be non-existent notwithstanding their numerical majority, for the simple reason that it is hard – if not impossible – to be consciously aware of them. Hence the illusion that our mental activity mainly consists of rational thinking, and hence the difficulty of apprehending how intuition 'works', unless one has a process model available.

3. The workspace formulation of mental processing

The previous section addressed the functions of elementary mental processes; this section zooms in on what happens inside these processes, and presents a strategy for formal process description. The approach followed here has been inspired by the 'free energy principle' introduced by Friston and his co-workers, which states that all the quantities in a system that can change, will change in order to minimize free energy (Friston & Stephan, 2007). The concept of 'free energy' originates from physics where it is employed in formal descriptions of the thermodynamical properties of gases in closed systems; it was later generalized in the context of machine learning to describe Bayesian inference of the sort implemented by predictive coding (Dayan, Hinton, & Neal, 1995; Rao & Ballard, 1999).

First, a generative mechanism will be proposed that all mental processes seem to have in common.

3.1. Signal generation by means of active noise shaping

As Section 2.4.2 described, stochastic itinerant neural activity – called noise here – is continually present in all circuits of the CNS. When a neural network selectively amplifies this noise, signal patterns emerge, seemingly 'out of the blue'. The network sustains those patterns as long as the amplification gain exceeds the signal losses.

A suitable metaphor is the laser. The word 'laser' is the acronym for: 'light amplification by stimulated emission of radiation'. The physical processes that operate inside the laser are described in the caption of Fig. 3; they have much in common with the neural processes that were just described, and they are well known.

Both in a neural network and in a laser the signal gain and the signal loss depend on several parameters: general process parameters, the properties of the amplifying medium and boundary conditions. Examples of general process parameters of a neural network are: the noise level, the neuromodulator concentrations and the energy supply situation; examples of medium properties are: the neural layout and the selective amplification characteristic or 'gain profile'.

For the laser process a prominent boundary condition is mirror reflectance. The influence of this boundary condition on the laser process can be understood in terms of how the light wave resonates within the stack of dielectric layers that each mirror consists of. Similarly the signal feedback delivered by a neural network could be described in terms of how the signal resonates in the network.

Of special interest is a phenomenon that I would call a

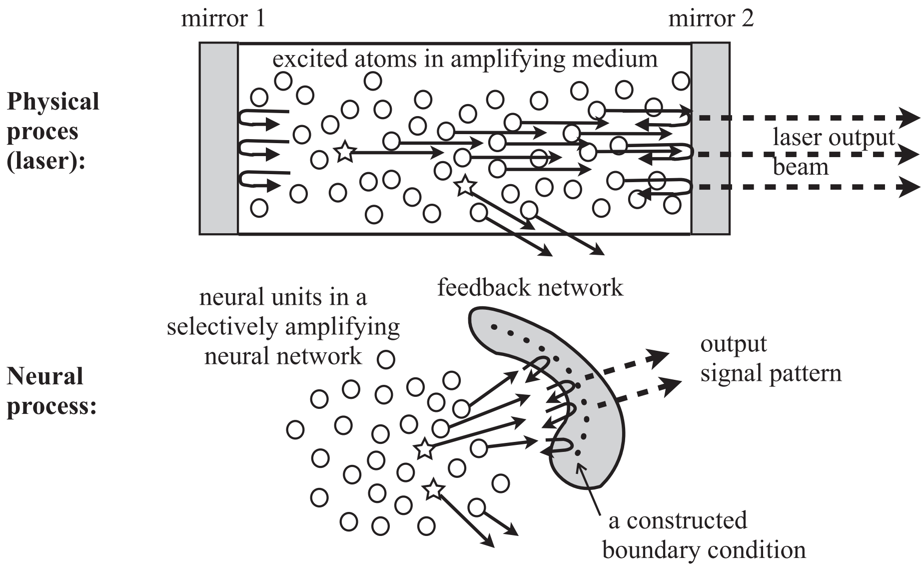

Fig. 3. Top: Laser process. In a laser medium atoms are excited, which means that in the atoms one of the outer electrons is brought into a specific high-energy state. During 'stimulated emission', the passage of a photon stimulates an excited atom to emit a second photon with the same wavelength, phase and direction. Both photons can, in turn, stimulate more excited atoms to emit a photon, and so on, so that an avalanche of photons emerges that aggregates into a coherent and monochromatic light beam. Spontaneously generated photons (symbolized by stars) trigger the avalanche. Accurately parallel mirrors at two sides of the laser reflect the beam. Any beam that is precisely perpendicular to the mirrors travels many times back and forth, and is amplified with every passage. The result is an intense light beam, a fraction of which passes through one of the mirrors and produces the laser output beam. The process of re-exciting atoms consumes energy; because the energy supply is limited, individual beams – each having its own specific wavelength – must compete for energy. The beam with the highest gain-to-loss ratio wins this competition. This is generally a resonating beam; resonance means that a multiple of one wavelength fits precisely between the mirrors so that the oscillations nodes of the wave coincide and the beam suffers minimum interference loss. Bottom: Neural process. Also in a neural network spontaneous signal generation occurs (symbolized by stars), and signal patterns are selectively amplified. A neighboring network is depicted that provides selective signal feedback, as is explained in Section 3.2.

'constructed boundary condition'. The feedback that a network can give to other networks depends on its resonance properties. So if the process that is active within this network has an influence on its resonance properties, that mental process modulates the network's feedback potential. The importance of this phenomenon lies in the fact that in this way processes in separate networks can impose temporary boundary conditions on each other. Predictive coding formulations of neuronal dynamics associate this phenomenon with attention (Feldman & Friston, 2010).

If the network can sustain several discrete signal patterns simultaneously, they must compete for the limited amount of energy that is available. Usually the competition process converges towards a state of equilibrium in which the signal pattern with the best gain-to-loss ratio dominates. A disruption of an existing equilibrium – for instance by the arrival of an unexpected sensory signal – means that the equilibrium needs to be re-established. Since in neural networks the process conditions that govern the competition vary continually, it may be expected that every new state of equilibrium will be different from the previous one.

I propose to call this dynamical process of signal generation and competition: a 'boundary condition-determined active noise shaping', or BANS process. To summarize, the occurrence of a BANS process requires the presence of: (i) iterant dynamics (noise), (ii) selective amplification, (iii) process boundary conditions, (iv) limited energy supply, and (v) signal competition. An example of a BANS process in the physical realm is the laser process described in Fig. 3.

An interesting example of the correspondence between the BANS processes in a neural network and in a laser concerns the concept of 'precision' that is employed in predictive coding descriptions of mental processes (Feldman & Friston, 2010). In my interpretation, precision is a measure of the selective amplification gain in a neural network. It mainly depends on two factors: the gain profile of the network and the selective strength of the signal feedback from surrounding networks. In analogy, the two main factors that determine the selective amplification gain or 'resonance quality' of a laser are: the gain profile of the laser medium, and the wavelength-dependent reflectivity of the mirrors. Therefore the resonance quality of a laser seems to be comparable with the precision of a neural network.

In this context it is interesting to note that – as Karl Friston pointed out to me – much of the theory behind self-organization and synergetics (Haken, 1981) derives from the statistical physics of lasers.

3.2. The two stages of a mental process

BANS processes are generative: they can create new mental entities, and they can eliminate (prune), alter and maintain existing mental entities. (A mental entity is defined here as a relatively stable signal pattern; an example is a thought that is paid attention to). Because a BANS process can 'make things happen' in a neural network, it can be seen as a driving power behind the process at system-level, in which system-level is the level of description where the focus is on the function of the mental process. This process engine is fueled by neurophysical mechanisms that are not discussed here. Since I am not aware of alternative mechanisms that have the same function, I assume that the BANS process constitutes the main system-level process engine in all mental processes.

Since BANS processes require the presence of boundary conditions for their operation, and since all mental processes depend directly on their process engine, in every mental process two components can be distinguished: its process boundary conditions, and the operation within those boundary conditions of a BANS process that brings about the functionality of the mental process. Since the creation of the first necessarily precedes the second, in this view all mental processes always operate in the same sequence: first the creation of boundary conditions, then the operation of a BANS process. Section 3.4 will discuss how this fixed process pattern leads to a formal process description.

Importantly, the characteristics of the two process components are quite different: the BANS process is a relatively simple and 'blind' generative mechanism, while the combination of boundary conditions can be highly complex. The latter determines for a large part the functionality potential that resides within the neural network, whereas the BANS process merely expresses that functionality in the sense that it makes the information contained in the network externally available in the form of an output signal pattern.

Important aspects of this approach were proposed earlier in Campbell's evolutionary epistemology that is based on the principle of blind variation and selective retention (Campbell, 1974). This mechanism is also found – as Campbell pointed out – in biological evolution where the emergence of complex biological organisms follows from a 'blind' struggle by generations of individuals – with only a limited behavioral repertoire at their disposal – for survival in a complex and merciless environment (Bickhard & Campbell, 2003).

3.3. The workspace formulation of mental processing

Also mental processes beyond the level of neural networks can be described in terms of interactions between BANS processes and their boundary conditions. For discussing those processes it is convenient to introduce the concept of 'workspace'. The workspace of a BANS process consists of the total of process conditions and boundary conditions that are relevant for the BANS process. Having this concept available makes it, for example, possible to state that a theoretical framework provides a suitable workspace for a scientific investigation, and that a well-posed question opens up a workspace for a discussion.

The size and scope of a workspace depends on the associated process task. For instance, the mental workspace provided by the culture of a society is of quite a different magnitude than the workspace that is used for preparing a simple action. A fundamental property of workspace is that one's total mental workspace – the sum of all the workspaces that are currently sustained within one's mind – imposes strict limits on what one can think of and learn, and on the actions that one can undertake. This is related to the assertion made in Section 2.2 that action preparation does not primarily aim at the physical environment but at the OFM.

Workspaces are often available for a longer period of time than is necessary for their use, either because they decay relatively slowly, or because they are maintained on purpose. An example of slow decay is the somatic response – defined in Section 2.5.1 – called rage, which can for instance be aroused by the suspicion that one has been fooled; rage may linger on for a considerable time. The culture of a society is an example of a maintained workspace; it lasts over many generations, while individuals adapt to it within a lifetime.

Now that the concept of workspace has been introduced, the two-stage description of mental processes presented in Section 3.2 can be given the more general formulation that I would call the 'workspace formulation' of mental processing: in all mental processes, an appropriate workspace is created first; then the operation within that workspace of a BANS process brings about the functionality of the mental process.

Here are some examples of the application of this formulation to some of the mental processes discussed earlier: (i) Prepared perception (Section 2.4.2) consists of: setting up a mental workspace related to a specific uncertainty in the OFM, followed by the orchestration – within that workspace – of a search for information in the environment. (ii) During an action decision process (Section 2.5.2), the OFM provides the environmental workspace for BANS processes that perform simulation activities. Subsequently, the outcomes of these activities set up a mental workspace for evaluation in which another BANS activity selects the most desirable action, which in turn sets up a workspace for the BANS process that orchestrates the execution of action.

Because most workspaces have a complicated organic (Section 2.6) structure, it is hard to be consciously aware of them. However, one may notice the mental effort that the maintenance of a workspace requires, or its inverse: the absence of an expected maintenance effort. The latter may explain the mental state called 'flow'. If the orchestration and execution of a complicated action are so well attuned to each other that the created workspaces are immediately used, then no workspace maintenance effort is noticeable, regardless of the difficulty of the task. In that situation flow can be experienced, i.e. the state of 'being fully immersed in a feeling of energized focus, full involvement, and enjoyment in the process of the activity […] characterized by complete absorption in what one does'. (Csikszentmihalyi, 1990)

3.4. Formal description of mental processes

The BANS process shares an interesting aspect with Bayesian probability calculus: both depend critically on an external factor and an internal factor. In the case of a BANS process these factors are the boundary conditions and the gain profile (Section 3.1), and in the case of probability calculus: the prior probabilities and the sensitivity function. This similarity has inspired me to formulate the following hypothesis: if it is possible to describe a mental process as an interaction between a BANS process and boundary conditions, then it should also be possible to describe that process in terms of probability mathematics, and therefore in terms of probabilistic inference in the brain. In the latter description the boundary conditions are represented by prior probabilities, and the gain profile by a sensitivity function.

If this hypothesis could be validated, then all the ingredients needed for formally describing mental processes are present: (i) a two-stage formulation that makes it possible to address every mental process in the same way, (ii) a matching formal description method, and (iii) a connected model of mental processing. Following on from this general basis, it may be possible to address a diversity of mental processes – such as action simulation, objectification, prepared perception, embodied valuation and the noise repair process – in a coherent fashion.

4. Discussion: how do signal patterns provide boundary conditions?

A remarkable phenomenon occurs in several of the mental processes discussed in this paper: a consolidation process forges a relatively stable mental entity from more evanescent and fleeting signal patterns. It is necessary to assume that such a process is active in order to explain how process boundary conditions are constructed (Section 3.3), how the serial mental processes that allow humans to reason and talk are created from organic processes (Section 2.6), and how the object concepts are constructed that build the OFM and thereby make anticipation possible (Section 2.2). So this phenomenon plays a crucial role in the proposed model of mental processing.

It may be possible to describe this consolidation process in terms of the interaction of a BANS process with boundary conditions, but the difficulty is that such would seem to lead to infinite regress: some of the boundary conditions are – according to this description – signal pattern consolidations that presuppose the activity of earlier BANS processes that operated in the context of still earlier consolidated boundary conditions, and so on. Of course no infinite regress takes place: every cascade has a neurophysical starting point. Such initiation may, for instance, follow on from a genetic or epigenetic predisposition that creates a workspace early in ontogenetic development, similar to the imprinting phenomenon seen in newly hatched goslings. Another possibility is that a noise signal pattern (Section 3.1) provides a suitable starting point by chance.

A more serious problem is that the mechanism underlying the consolidation process is unclear. Two other basic processes that were discussed earlier in Section 2.4.2 are problematic in a similar way: (i) the detection of uncertainty within the OFM on which the initiation of prepared perception relies, and (ii) the measurement of OFM coherence on which the noise repair process rests. Gaining a better understanding of the underlying mechanisms would be highly relevant for the further development of the proposed process model.

5. Results and conclusion

This paper develops a theoretical framework consisting of three parts: a process model – in which the 'organic forward model of the environment' plays a central role –, a general view of mental processing called the 'workspace formulation', and a strategy for formally describing mental processes. Although the aim of this framework is to create a suitable workspace for investigating prediction in action, the framework may also be useful for investigating mental processing in general.

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